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THESIS

SECURE FLIGHT-DECK COMMUNICATIONS

by

Serhat Ahmet Bac

December 1974

Thesis Advisor: D. B. Hoisington

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The system was demonstrated by building a portion of a complete system on a simulated steel flight-deck.

Secure Flight-deck Communications

by

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requirements for the degree of

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ABSTRACT

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The system was demonstrated by building a portion of a complete system on a simulated steel flight-deck.

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I. INTRODUCTION

Despite the degree of sophistication modern communications technology has attained, the problem of security still poses serious threats to military forces operating in hostile environments. The problem manifests itself in all scales of systems, whether it be large data communications networks or in the simplest two-way radio link.

Realizing a secure or covert communications network usually necessitates the use of extremely complex hardware (and sometimes software) configurations which at times can be rather extensive in physical space consumptions, cause reliability problems and increase the cost of a system by a considerable amount. In the case of large-scale communications systems, the security obtained may greatly outweigh these apparent disadvantages, thereby justifying employment of such a scheme.

However, large systems are not the only types which may require some degree of security, since an application in which a small single channel circuit is utilized may have need for some type of cover also. When considering a small system, the tradeoffs mentioned above do not follow the same set of ground rules since compactness and portability are usually prime criteria. Cost may also be a major factor. Certainly the full cover utilized in larger systems would be attractive in smaller units as well, but the complexity involved in the realization of such a scheme simply does not

lend itself to efficient solution on a smaller scale. The main question that arises then is one of whether or not a small communications system can be provided with the ability to make impossible hostile interception to the transmitted signal. The working device that resulted from this study is one answer to this question.

A. STATEMENT OF THE PROBLEM

Many present military operations are coordinated by means of voice transceiver networks which vary in complexity from single to multiple-channel systems. In this thesis the study was concentrated on the case which dealt with communications on the flight-deck of an aircraft carrier. The basic premise was that regardless of the apparent importance of any transmitted information, the interception of the signal could cause the location of the unit to be pinpointed to a hostile party and provide a means for a hostile aircraft or missile to home onto the carrier. The necessity of making impossible hostile interception of this signal was the driving force for this thesis.

B. DEFINING THE PROBLEM

At this point a simple premise can be invoked: if the enemy is unable to detect the signal being transmitted, he will then be unable to find the carrier by means of the transmission. With this hypothesis accepted, the problem falls into the realm of transmission security, or covert communications, and the problem can be concisely stated: "Devise a system for flight-deck communications from which

there is absolutely no detectable radiation that could be used for homing by enemy aircraft or missiles."

1. General Considerations

The general nature of the problem statement presented a range of selections for the specific thesis application. The approach decided on was to design and build a working model which would completely realize the theory involved, while at the same time would not represent a purely theoretical research effort. With this in mind, the problem then became the design and construction of a voice modulator-demodulator (MODEM) transceiver with an output/input stage providing coupling to the desired receiver without producing a radiation field.

For the purpose of communications, a series and parallel configuration of coils was considered to be placed on the flight-deck. The total size of this assembly of coils was smaller than the wavelength which was dealt with (6,000 meters for the carrier frequency of 50 KHZ). The size of a single coil was then much much smaller than a wavelength. This small size became a major factor in minimizing the radiation. Indeed, the calculations presented in Appendix A of this thesis show that the vertical component of the electric field for a single coil is undetectably small, even at very short distances from the coil. A plot of electric field vs. vertical distance from the coil is shown in Figure 17.

In addition, the unit coils were coupled in such a way that the polarization would be opposite for adjacent

coils, providing a cancellation of the radiation from adjacent coils in the far-field.

The second set of criteria considered was that of compactness, reliability, low cost and simplicity. Compactness indicated that the use of integrated circuitry (IC) would be required and specifically the use of standard "off-the-shelf" integrated circuits would enhance reliability and minimize the cost. Simplicity would then follow as a natural result since integrated circuits allow the system to be designed in functional modules, as opposed to integrating many discrete components.

To obtain communications on a radio-frequency carrier it is necessary that some type of modulation process be employed. The requirements of eliminating (in the worst conditions, reducing) interference at the receiver on a carrier flight-deck where radio-frequency noise is a problem, and of the utilization of a simple and inexpensive modulation equipment, led to the decision to use narrow-band frequency modulation (NBFM) techniques.

The carrier frequency which was selected had to be in the low-frequency (LF) region (50 KHZ for experimental purposes) to minimize the possibility of radiation from the system.

The next step was to design and construct the circuitry required to realize the concept. This is described in Part III of this thesis.

II. DISCUSSION OF THE COUPLING SYSTEM

A. REQUIREMENTS

1. Elevation of Coils Above the Steel Deck

The first criteria to be considered was the inductance of a unit coil. Any drastic change of this inductance with frequency would also cause the quality factor (Q) and the bandwidth of the coil to vary, thus minimizing the reliability of communications.

For the purpose of inductance measurements the set-up shown in Figure 1 was used. The two sets of data taken corresponded to the inductance of the coil when the coil was placed on the steel plate and 1.5 inches above it, respectively, for a range of frequencies from 5 to 100 KHZ.

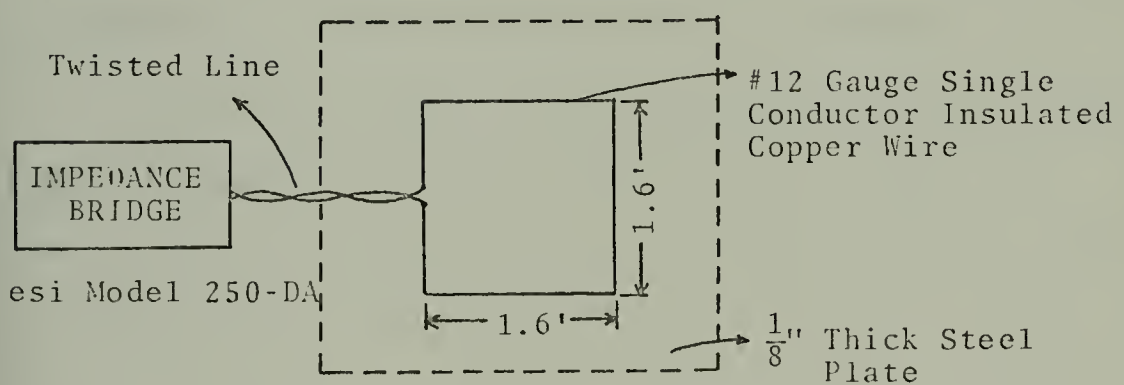

Figure 1. Set-up for Inductance Measurements.

To measure the inductance at this frequency range an impedance bridge (esi MODEL 250-DA) was utilized. This bridge had limited accuracy in the range from 10 to 100 KHZ. The problem of inaccuracy in the measurement was not of a great importance however, since the change of inductance with

respect to frequency was the point of interest rather than the precise value of inductance at every frequency. The plots of the inductance of the coil vs. frequency for two heights are shown in Figure 2.

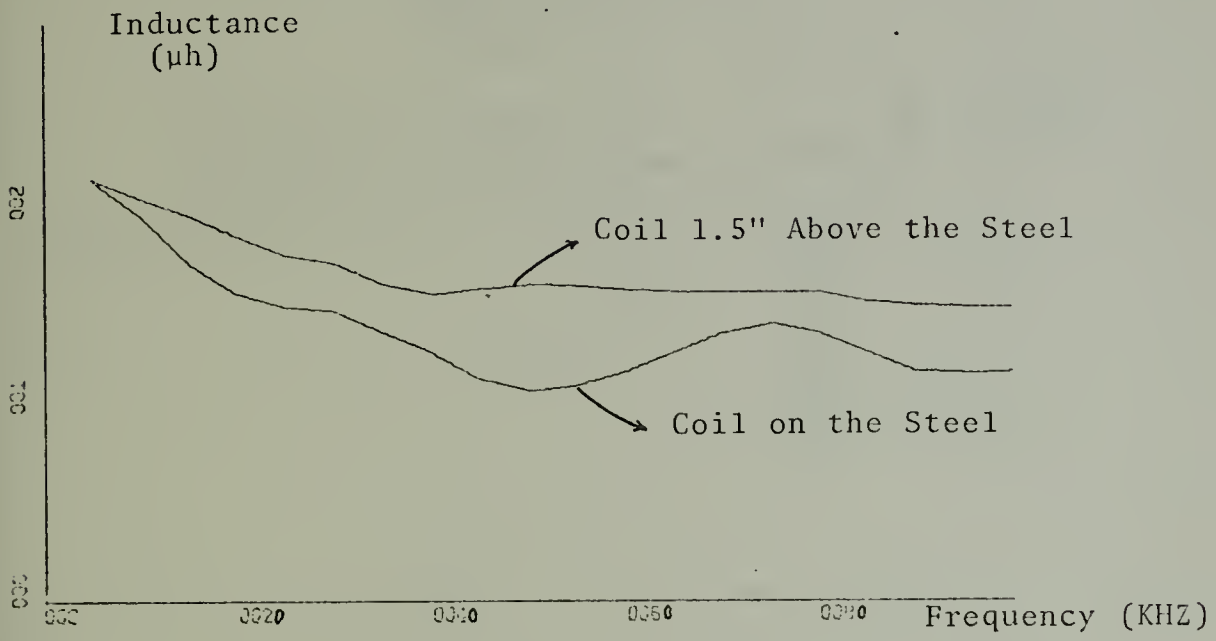

Figure 2: Inductance of the Coil vs. Height.

From these plots it was seen that when the coil was placed 1.5 inches above the steel plate, its inductance showed a more uniform distribution over the frequency range in interest than in the case where the coil was in touch with the steel plate. From this point on, all the experiments were conducted using the coil(s) 1.5 inches above the steel plate.

2. Energy Transfer by Means of Inductive Coupling

The second set of criteria to be considered was whether or not an energy transfer between the coil and a small pick-up coil could be possible by means of inductive

coupling and the strength of this transfered energy would be of a detectable level. The arrangement shown in Figure 3 was utilized to measure the value of the induced signal.

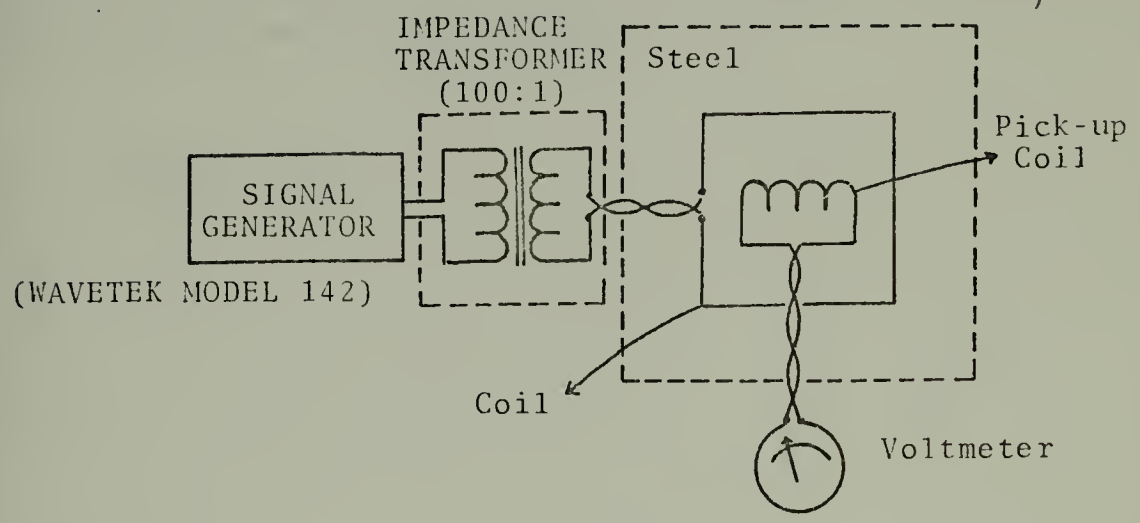

Figure 3. Measurement of the Induced Signal.

Because of the very low impedance of the coil (0.5 ohm @ 50 KHZ) an impedance transformer with a turn ratio of 100 to 1 was used to couple the signal generator with 50 ohm output (WAVETEK MODEL 142) to the coil.

The results of this measurement, plotted in Figure 4 for frequencies up to 100 KHZ, showed that a detectable signal could be obtained above 20 KHZ with a very low input power, and the signal became stronger with increasing frequency.

3. Coupling vs. Position of the Pick-up Coil

For a reliable communications system it was evident that the coupling between the assembly of coils placed on the flight-deck and the pick-up coil carried under the shoes

of flight-deck personnel had to be reasonably independent of position of the pick-up coil. The omission of this requirement would limit the movement of flight-deck personnel, necessitating transmitting and/or receiving to be done in a fixed position on the flight-deck.

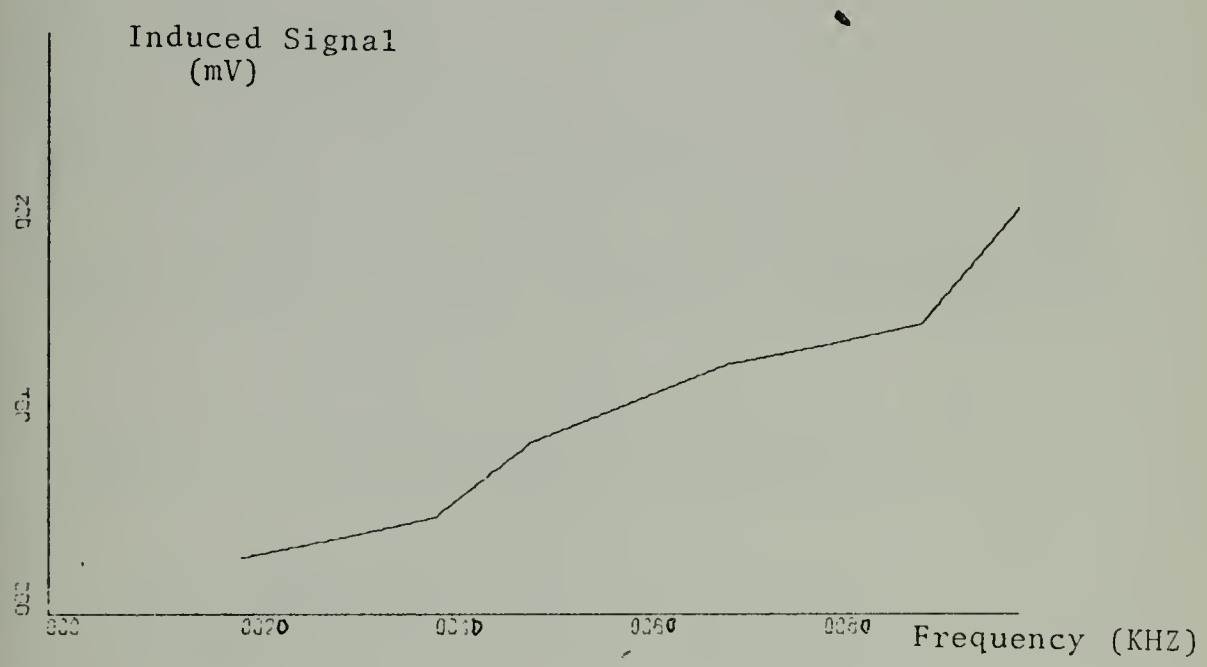

Figure 4. Induced Signal vs. Frequency.

The measurements of the induced signal at the pick-up coil with increasing distance from the coil toward its center, and increasing height from the plane of the coil along the center axis showed that a coupling reasonably independent of the position of the pick-up coil could be obtained. The results of these measurements for different frequencies are plotted in Figures 5 and 6, respectively.

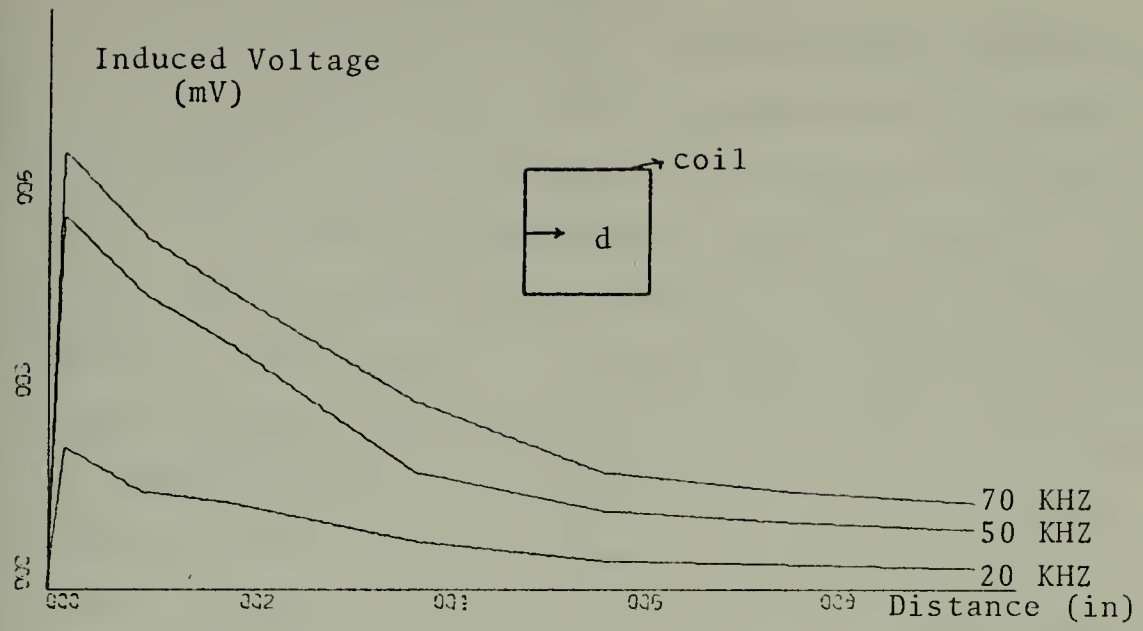

Figure 5. Induced Voltage vs. Distance from Coil.

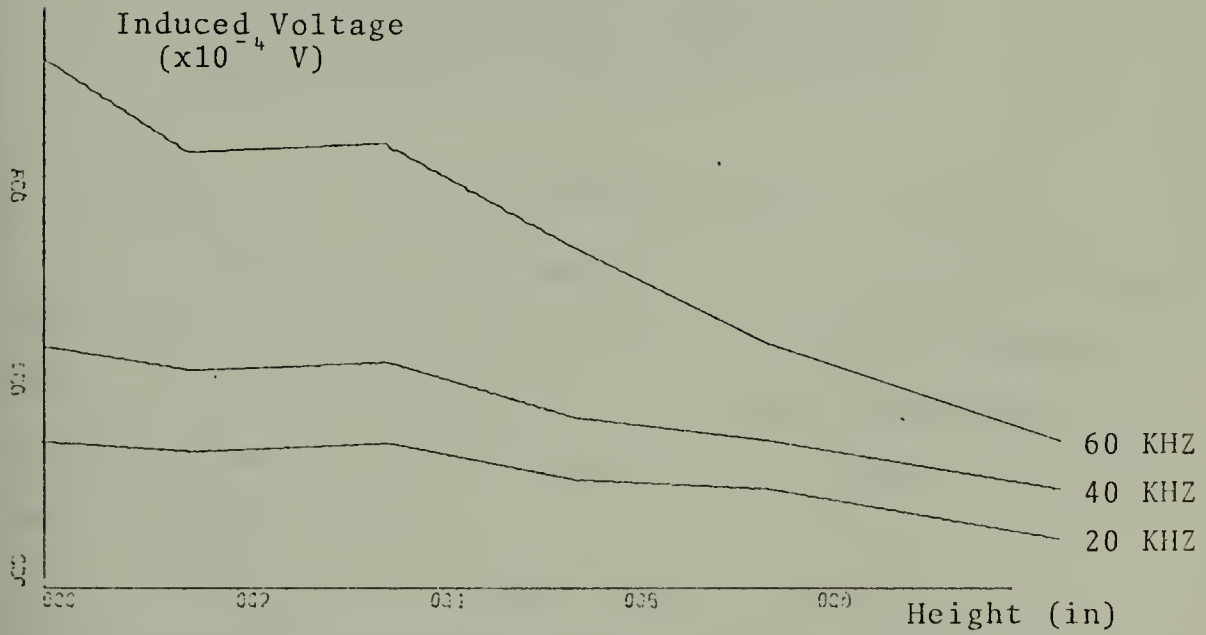

Figure 6. Induced Voltage vs. Elevation of Pick-up Coil Along the Center Axis.

B. COIL SYSTEM DESIGN

1. Physical Considerations

In accordance with the study previously presented, it is to be remembered that the coils had to have a certain elevation above the steel flight-deck to obtain more uniform results over a band of frequencies. This is obviously a factor which limits the use of the system on a steel flight-deck without a wood overlay. A possible solution to the problem might be to use a coil configuration with the coils placed in channels opened on the flight-deck, as shown in Figure 7. After the coils are laid, these channels can be filled up with a hardening solvent for the use of the flight-deck. It is to be noted that this scheme would require further investigation of its feasibility.

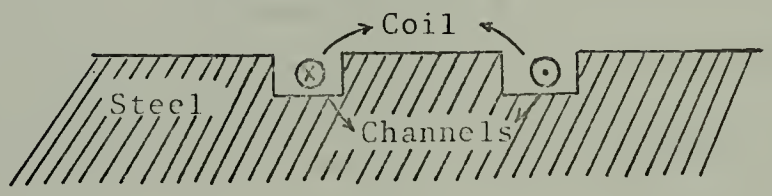

Figure 7. A Scheme for the Placement of Coils.

Furthermore, the nonskid material covering the steel deck and the dense number of light-water nozzles and tie-downs spread over the area of flight-decks require the use of the system on a future aircraft carrier rather than the ones in service today.

Here, it is to be mentioned that the possibility of communications using frequency modulation techniques with the coils placed directly on the steel flight-deck was left as an

open area for further investigation. If reliable communications were to be obtained with this scheme, then the placement of coils on the steel deck (under the nonskid material) could possibly be applicable to today's carriers.

2. Coupling of Coils

As mentioned earlier, to obtain a cancellation of radiation from adjacent coils, these coils had to be oppositely polarized. A method for obtaining an opposite polarization for every adjacent coil can be a series coupling between them as shown in Figure 8 for four coils.

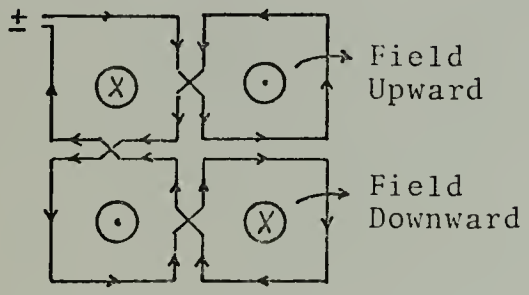

Figure 8. Series Coupling of Four Coils with Polarization.

At this point, it is not to be forgotten that reliability of communications system was also a major requirement to be realized, as well as security. With this in mind, one can state that the system is far from being reliable with this series configuration of coils. Indeed, the flight-deck of an aircraft carrier is likely to be damaged in every kind of environment (hostile or friendly), and a break in any coil of the series configuration will cause a loss of the communications.

A solution for the requirement of reliable communications can be stated to be a series and parallel coupling

between the coils as shown in Figure 9. With this series-parallel configuration, if one coil is damaged, there is still a chance to communicate reliably, except in the strip of coils where the damaged coil is located. Also, it is necessary that the output line from the island of the ship must be coupled to the system by using an impedance transformer, because of the very low impedance of the parallel configuration of strips of coils.

The completed coil system is presented in more detail in Part III-B of this thesis.

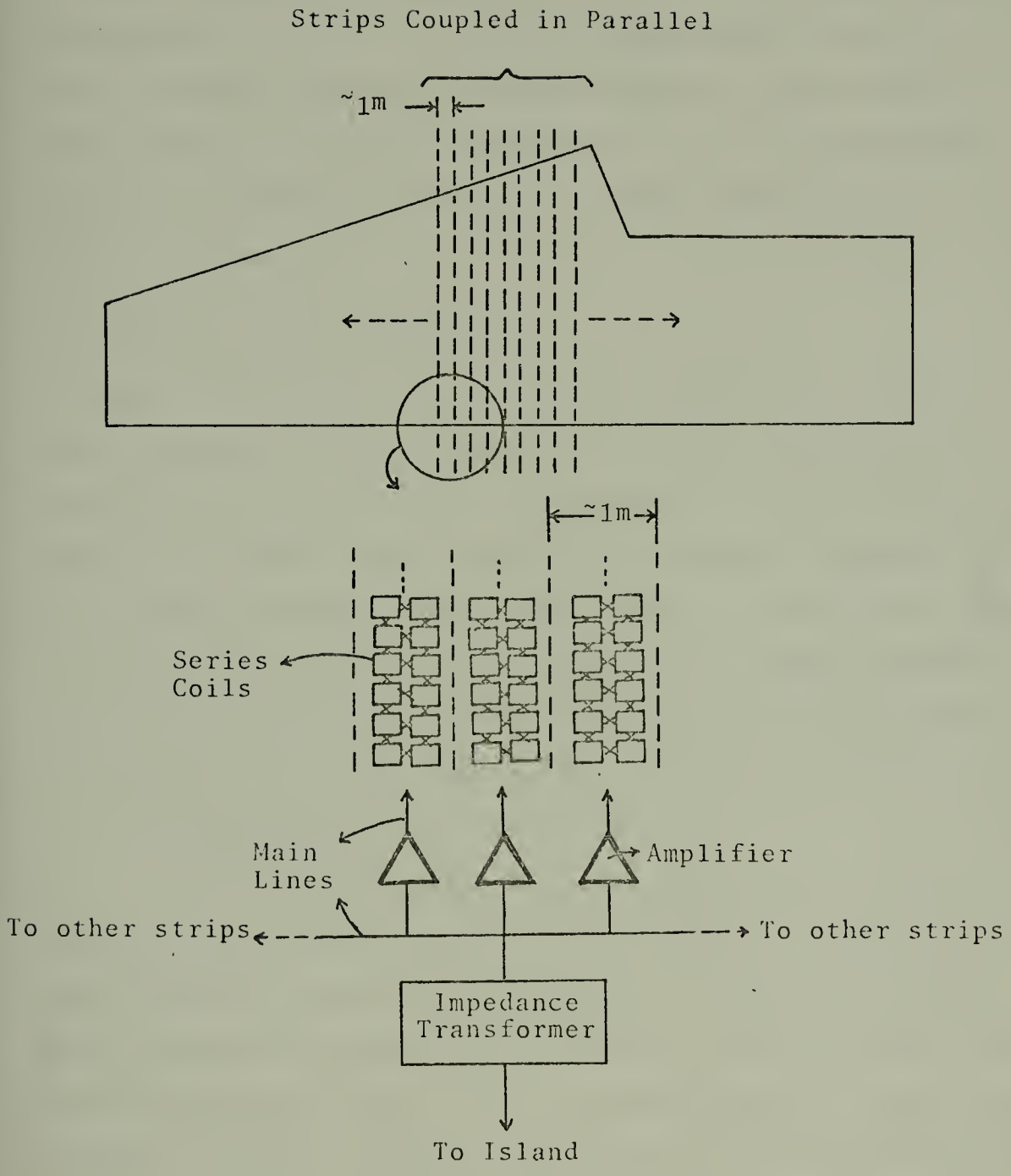

Figure 9. Series and Parallel Coupling.

III. SYSTEM DESIGN AND RESULTS OF EXPERIMENTS

System design was predicated on the criteria previously mentioned. That is, it is to be a working model which employs inductive coupling between transmitter and receiver stages without producing a radiation field, and narrow-band frequency modulation techniques to obtain communications on a radio-frequency carrier.

A. OVERALL SYSTEM DESCRIPTION

Figure 10 depicts a general block diagram of a complete communications system. Basically, the audio signal is modulated on a carrier suitable for transmission, fed to the transmitter stage in this form and is then sent out over the coil system previously discussed. At the receiver the signal is received by means of a pick-up coil, the proper frequency band is selected and fed to the inverse processing hardware, which detects the signal and converts it to an audio output.

1. Transmitter

In order to process the audio signal into a form suitable for transmission, this audio signal is first amplified, amplitude limited to eliminate noise spikes and limit audio amplitude, and band-pass filtered from 300 HZ to 3 KHZ. This band-limited signal then frequency modulates a sinusoidal carrier of 50 KHZ, which in turn is amplified before being fed to the coil configuration. The transmitter block diagram is shown in Figure 11. For experimental purposes a WAVETEK MODEL 142 oscillator was used for the modulation and RF amplification

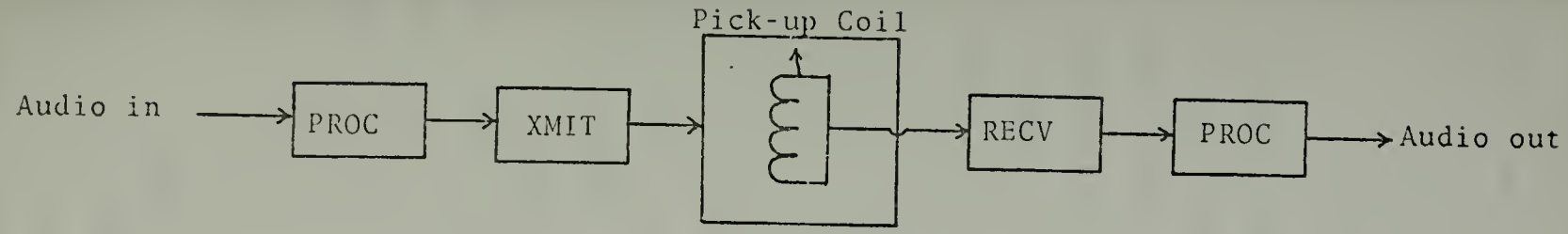

Figure 10. Overall System Block Diagram.

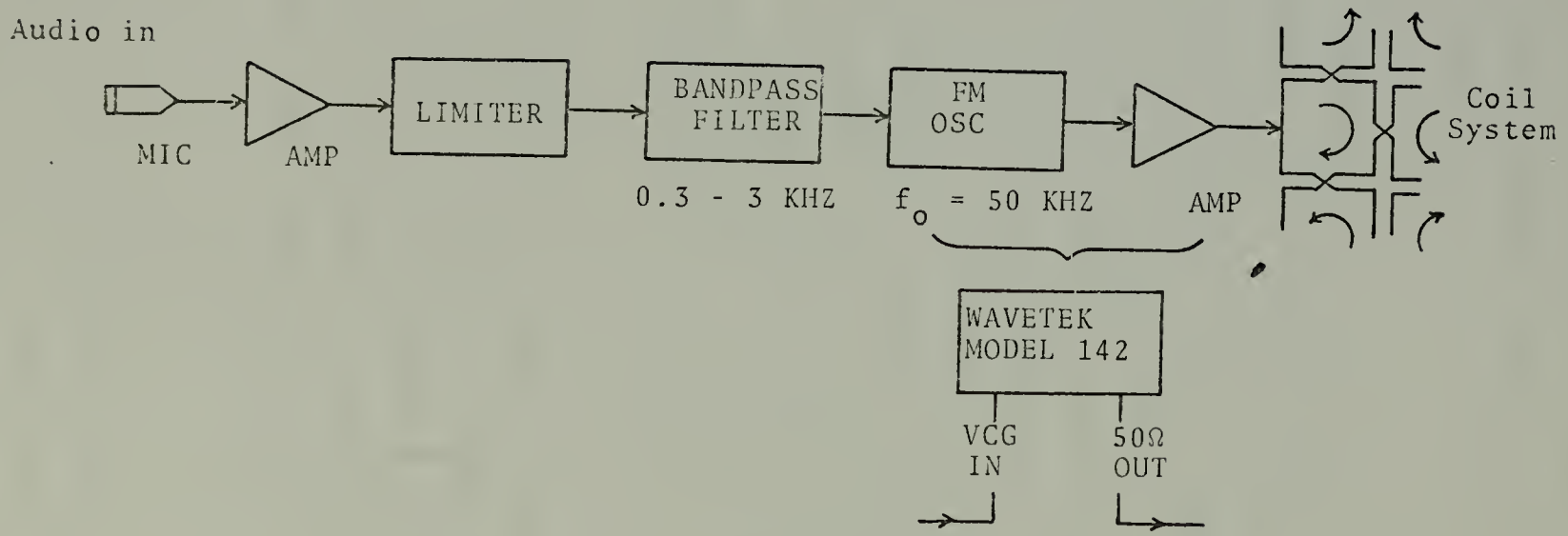

Figure 11. Transmitter Block Diagram.

process. To band-limit the audio signal, an active filter (second order Butterworth filter) was utilized to obtain a closer approximation to the ideal bandpass response than a regular RC bandpass filter would give.

2. Receiver

At the receiver the signal is received by a pick-up coil and amplified to a detectable level. Then the proper frequency band is selected using a bandpass filter. Again, this filter is active (second-order Butterworth) for a sharper cut-off. Since the received signal is a narrow-band FM signal, it is composed of a carrier and a single pair of sidebands with frequencies $w_c \pm w_m$. As mentioned earlier, the modulating signal (audio signal) has a maximum frequency of 3 KHZ. This led to the decision to build an active band-pass filter with a bandwidth of 6 KHZ, namely, from 47 KHZ to 53 KHZ for a carrier frequency of 50 KHZ. The band-limited FM signal is then limited, detected, and preamplified for audio output.

The block diagram of the receiver is shown in Figure 12. Again, for experimental purposes, Fairchild's MODEL CA 3075 chip is utilized for the detection of the audio signal. This system consists of a limiting amplifier, a differential peak detector and an internally biased audio preamplifier (Refs. 4 and 5).

3. Power Considerations

To measure the required power for communications, two sets of experiments were conducted. First, a single coil was connected to the transmitter and the output of the transmit

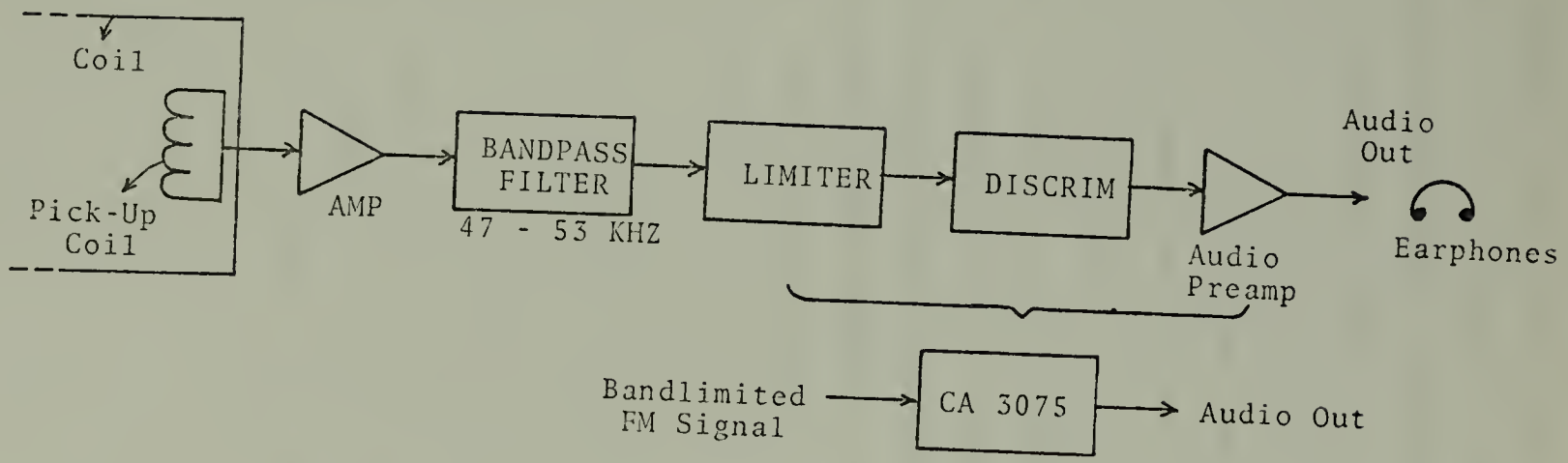

Figure 12. Receiver Block Diagram.

stage was increased until a detectable signal could be obtained at the center of the coil where the weakest field existed. At that instant the volt-ampere product was determined to be 2.56 mV-amps. Then the same procedure was repeated, but this time using four coils in series, connected to the transmitter as shown in Figure 8. The required power for a detectable signal for this experiment was measured to be 2.65 mV-amps. In the preliminary measurements, it was seen that the impedance of four coils in series was four times greater than the impedance of a single coil for the frequency range from 5 KHZ to 100 KHZ. The measurements mentioned above showed that the power did not follow this linearity with the increasing number of coils. Then, it was decided that this nonlinearity could be explained by iron losses on the steel plate caused by edge effects which increased the amount of required power in the case of the experiments performed using a single coil.

In the previous part of this thesis it was mentioned that a possible coil system design would be a series and parallel coil configuration, that is, a number of series coils would be coupled in parallel strips by means of main lines. If the strip located at the widest part of the flight-deck (with a starboard-port width of 230 feet) was taken into account, an approximate number of 140 unit coils could be calculated, if every strip contained only one line of coils in series. (This number was obtained using the dimensions of the square coils experimented with, namely, 1.6 feet.) But it was decided that a reasonable strip width where a loss of communications caused by any damaged coil would not affect

the whole communications system greatly, could be about one meter. With this in mind, every strip resulted in having two lines of coils in series per strip, in other words, 280 coils per strip, or less. (Here, it is to be noted that these figures are subject for further investigation.)

At this point, a statement was to be made that reliable communications on one strip of coils could be possible using a very small amount of power (less than 1 V-amp) due to the required power not being proportional to the increasing number of coils. This statement was also true for the assembly of strips of coils, since the signal would be amplified before being fed to every strip, as shown in Figure 9, thereby increasing the signal power to a detectable level in each strip.

B. COMMUNICATIONS IN THE REVERSE DIRECTION

Up to this point only a communications scheme from the island of the ship to the flight-deck has been discussed. It is obvious that a system designed on a one-way communications basis is incomplete for operational and tactical purposes on an aircraft carrier, and an improvement of the original system by which communications in the reverse direction will be possible is needed.

The first criteria to be considered was whether or not a coupling between the pick-up coil and the coils on the deck would result in reliable communications if an FM signal was directly fed to the pick-up coil. Once this possibility is realized, then communications from deck to island and from

deck to deck would be possible, since the flight-deck personnel could carry the transmitter as well as the receiver.

Experiments performed with four coils in series showed that this possibility was true, even with the same amount of power as required in the previous case where the signal had been fed to the coils. This factor led to the decision to assemble the transmitter and the receiver to form a transceiver MODEM. The completed device is shown in block diagram in Figure 13.

The second criteria was the proper coupling of the strips to obtain communications from deck to island and deck to deck. One of the major problems to be solved was the very low impedance of the strips caused by parallel coupling. This led to the decision that an impedance transformer was required at the output of every strip. With this scheme, the impedance of a particular transmitting strip could be matched to the impedance of the rest of the configuration. But in the receiving mode for this particular strip, the signal had to by-pass the impedance transformer located at its output, since the impedance matching was achieved by the transmitting strip itself.

Moreover, every strip needed a transmit and a receiving amplifier at its output to realize communications using a very low amount of transmitted power, as discussed earlier. These factors necessitated the use of different input and output signal paths for each strip.

One possible scheme to accomplish this is shown in Figure 14, where a functional diagram of the parallel coupling

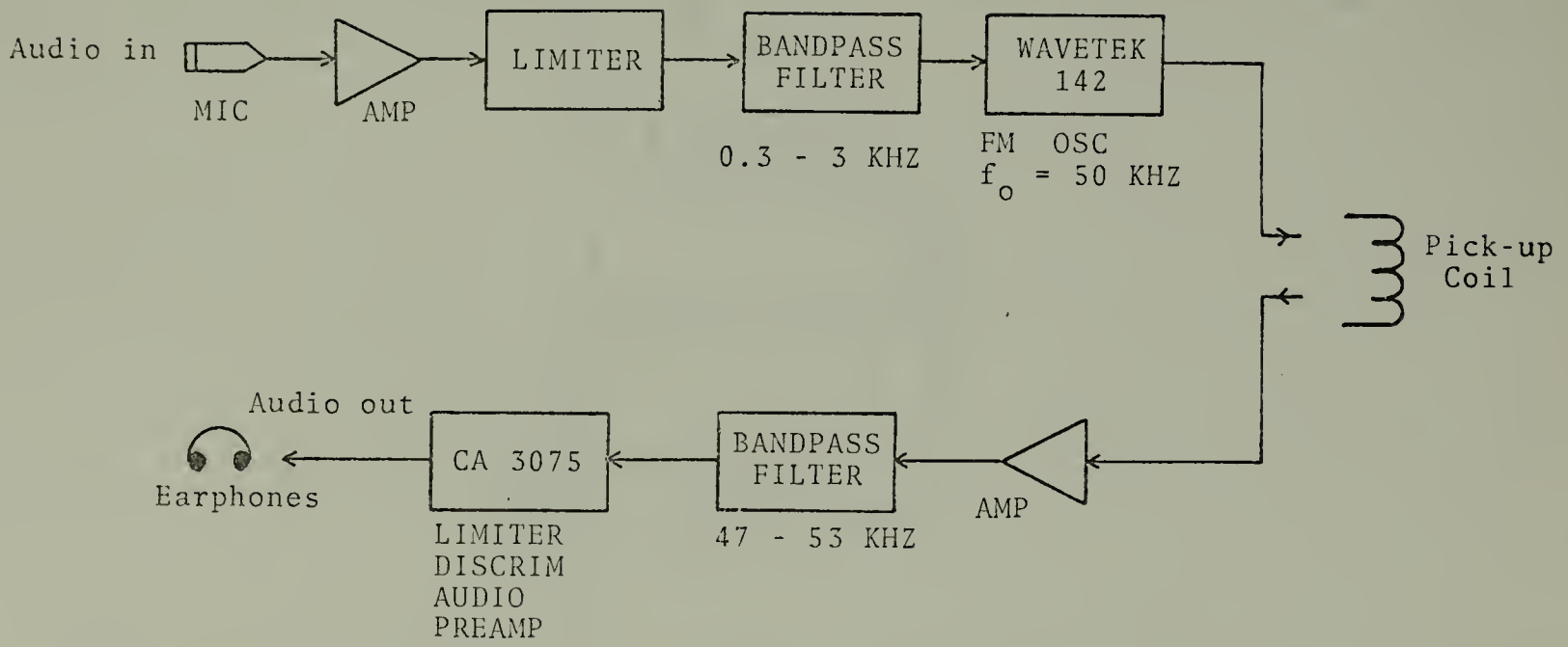

Figure 13. Transceiver Block Diagram.

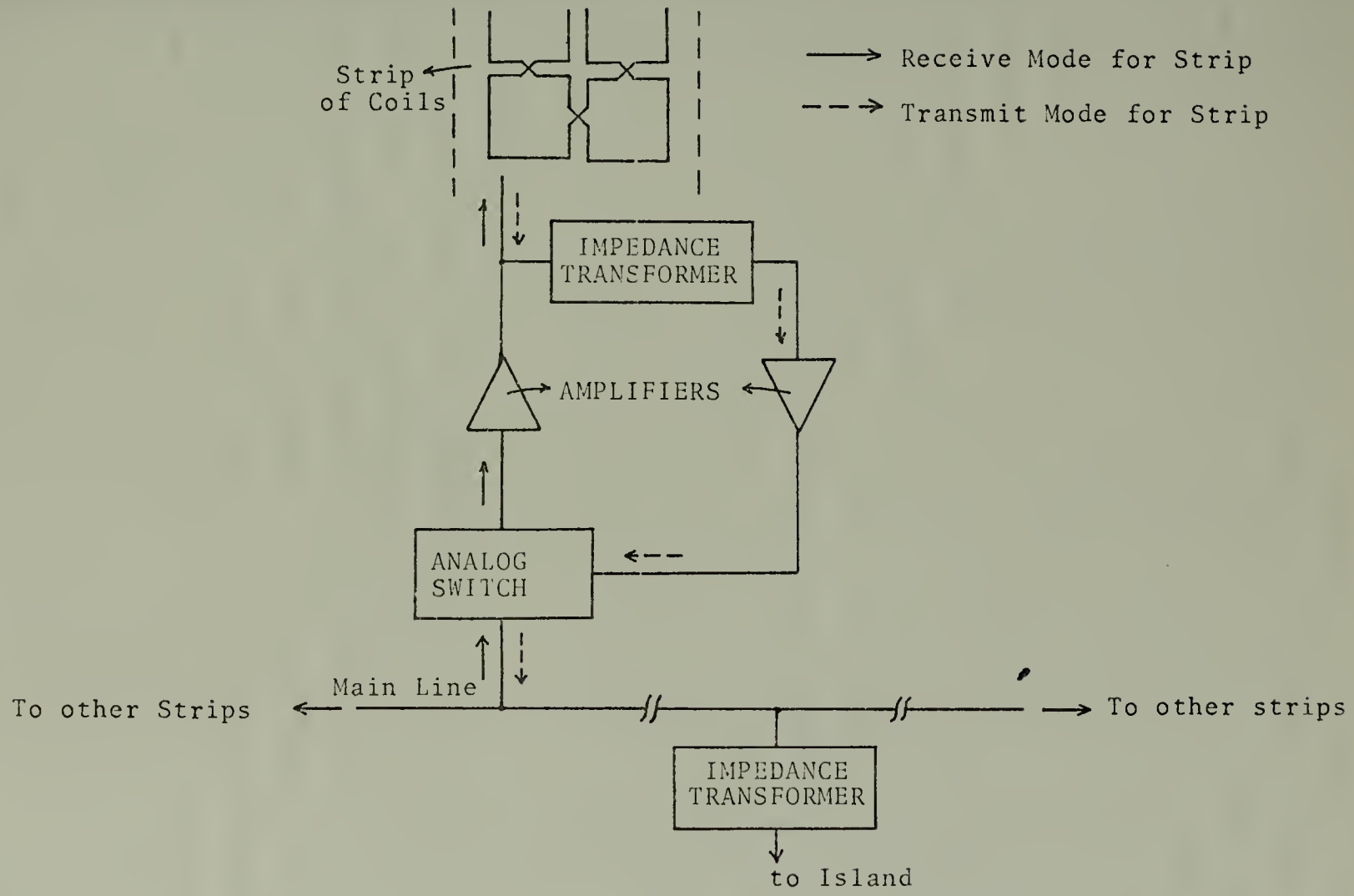

Figure 14. Parallel Coupling of Strips.

system for a single strip is presented. The signal transmitted from the strip passes through a loop which includes an impedance transformer and an amplifier. On the other hand, for the receiving mode, the signal follows another path where a receiving amplifier is located. These two branches are connected to the main line leading to the rest of the system, by means of a voltage controlled analog switch. When the strip transmits, this switch removes the receiving amplifier and connects the impedance transformer and the transmit amplifier to the main line. In the receiving mode for the strip, it disconnects the transmit path from the main line and allows the signal to pass to the strip through the receiving amplifier. The main objectives of the study dictated that the detailed design of the voltage controlled analog switch would be left as further investigation subject.

C. OPTIMUM COIL SIZE

The experiments done throughout the study showed that there was a loss of communications when the pick-up coil was placed symmetrically above the coils which carried a current flowing in the same direction, as shown in Figure 15 for different coil spacings. This was due to the cancellation of the currents induced in different directions in the pick-up coil, thereby creating a number of trouble spots in the coil system. One solution to this problem was to devise a system with two inputs from pick-up coils placed under both shoes and which would operate on the stronger signal, no matter what polarity.

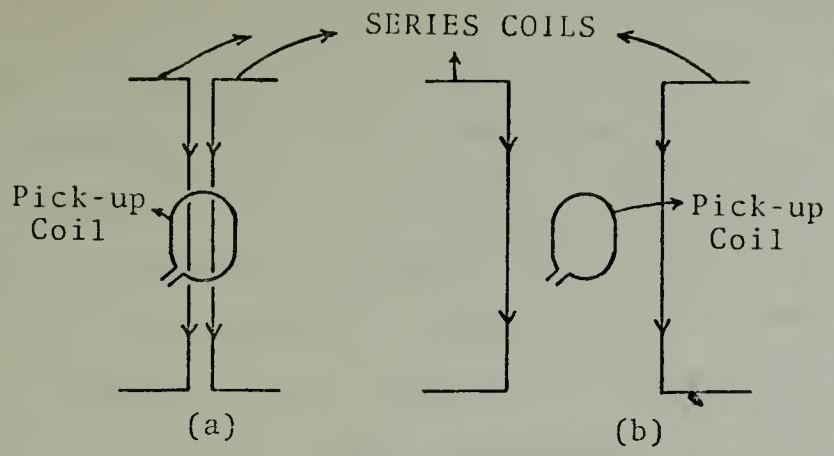

Figure 15. Trouble Points for Different Spacing of Coils.

The system shown in Figure 16 is one possible circuit which will select the stronger induced signal and pass it to the receiver by means of two analog gates and a trigger circuit. Again, not to interfere with the main objective of this study, the detailed analysis of this circuitry was left as further investigation subject.

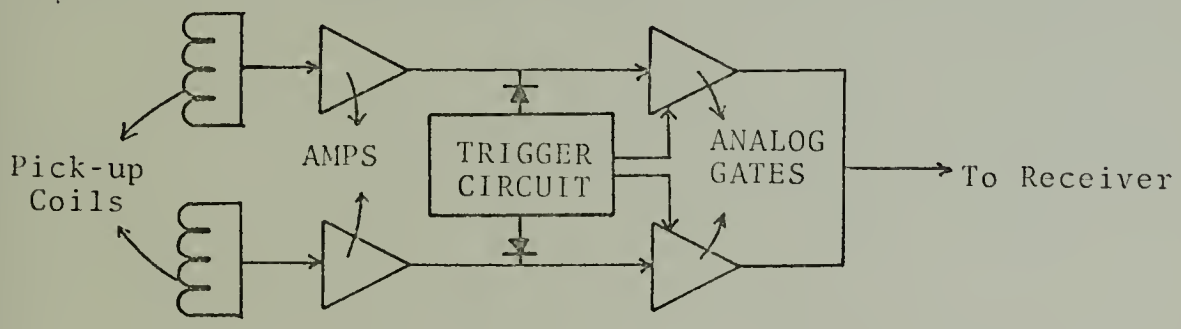

Figure 16. A Possible Scheme to Select the Stronger Signal.

At this point, it was decided that the probability of at least one pick-up coil being out of trouble points was a question to be considered. This, of course, manifested itself as a function of the number of trouble points on the deck, accordingly as a function of coil size. The larger the coils were, the smaller would be the number of trouble

spots on the deck, thus giving a greater probability of obtaining a signal with either one of the pick-up coils. But this hypothesis had a limitation, namely, power requirements. It was shown in Part II-A (3) and Figure 5 that the intensity of the field decreases in the center of the coils. It is evident that the bigger the coils, the more power needed to feed the coils in order to have a detectable signal at the center of each coil. Then, it was decided that the optimum coil size would only be defined by the tradeoffs mentioned above.

As a future investigation, one way to arrive at a conclusion on the optimum coil size will be to go through the same procedure of experiments conducted in this study, but using larger coils and to measure minimum amount of power required for a detectable signal in every loop of coil.

IV. CONCLUSIONS

At the outset of this report, the statement was made to the effect that the finished product was to be a working model which would illustrate a technique whereby a frequency modulated carrier by an audio signal could be transmitted and received using inductive coupling, thereby giving the feature of covertness to a simple transceiver network. The actual MODEM developed does indeed fulfill these requirements, as has been illustrated in the preceding sections.

In addition to fulfilling the requirements concerned with circuit design, reliability and simplicity, the added feature of an efficient coil configuration also evolved from the study. The total size of this coil configuration being much smaller than the wavelength of the transmitted signal minimizes the radiation. Moreover, the opposite polarization of adjacent coils provides a cancellation of the radiation from these coils in the far-field, thereby giving the feature of security to the total system.

A portion of the complete system built for experimental purposes demonstrates the theory required for the eventual design and construction of the actual communications system. Since the groundwork for secure flight-deck communications has been solidified by the realization of this transceiver and coil design, it is appropriate at this time to recommend topics of possible follow-on work which would be pursued toward the complete problem solution.

The first area of concern is that the communications system in its present state uses coils about 1.5 inches above the steel deck. Thus a wooden overlay is required on the flight-deck for mounting of the coils. Although the inductance of an elevated coil showed a more uniform distribution over the frequency range in interest than the inductance of the one placed on the steel, as presented in Figure 2, an area of future investigation still exists, namely, the possibility of reliable communications using frequency modulation techniques with the coils placed directly on a steel deck. If this scheme gives better results than the one previously tried, then the placement of coils will be much easier and applicable to carriers in service today having steel flight-decks without a wood overlay.

A second area of possible improvement is the method of coupling the coils. The present method uses series coils coupled together in parallel strips along the width of the deck with a highly dense circuitry (main lines, amplifiers, impedance transformers, etc.). A possible improvement would be to use elliptic strips of series coils covering the flight-deck, or a configuration of strips placed along the length of the deck, instead of the width, thereby decreasing the number of strips. Evidently, this decreased amount of strips would require less circuitry for parallel coupling between the strips.

In addition, the usable deck area could be calculated excluding catapults and elevators, and/or the shape of coils could be changed from square to rectangular, theregy rendering

the communications to be realized with a minimized number of coils, accordingly with a less amount of required power.

The third consideration is, of course, design and fabrication of the transceiver. An improved device could be built with capability of operating in several communications channels. This would be possible by designing an FM oscillator which would produce different carrier frequencies in the LF region, and a receiver bandpass filter with the ability of selecting more than one frequency band for eventual detection. Thus several communications channels could be provided with no interference between channels.

In any event, the initial task of demonstrating a secure flight-deck communications technique has been realized, and it is the hope of the author that future research and development will eventually lead to a complete operational system.

APPENDIX A: CALCULATION OF THE VERTICAL COMPONENT OF THE ELECTRIC FIELD RADIATED FROM A SINGLE COIL

The following equation is obtained from elementary-dipole theory and is applicable to low-frequency antennas. It assumes that the earth is a perfect reflector, the antenna dimensions are small compared with λ, and the actual height does not exceed $\frac{1}{4}\lambda$.

The vertical component of electric field radiated in the ground plane, at distances so short that ground attenuation may be neglected (usually when $D < \lambda 10$), is given by

$$E = 377\ I\ h_e\ /\ \lambda\ D$$

where

E = field strength in millivolts/meter,

I = current at base of antenna in amperes,

h_e = effective height of antenna,

λ = wavelength in same units as h_e, and

D = distance in kilometers.

For a loop antenna the effective height can be calculated by the following equation:

$$h_e = 2\pi\ n\ A\ /\ \lambda$$

where

A = mean area per turn of loop and

n = number of turns.

Using the numbers obtained in the measurements throughout the study, the electric field strength was plotted as a function of increasing distance from the coil in kilometers. This

plot, which is presented in Figure 17, shows that the electric field radiated from a single coil is at an undetectable level (actually buried in noise), even for very short distances. ($E = 2.306 \times 10^{-9}$ V/m @ 1 km.)

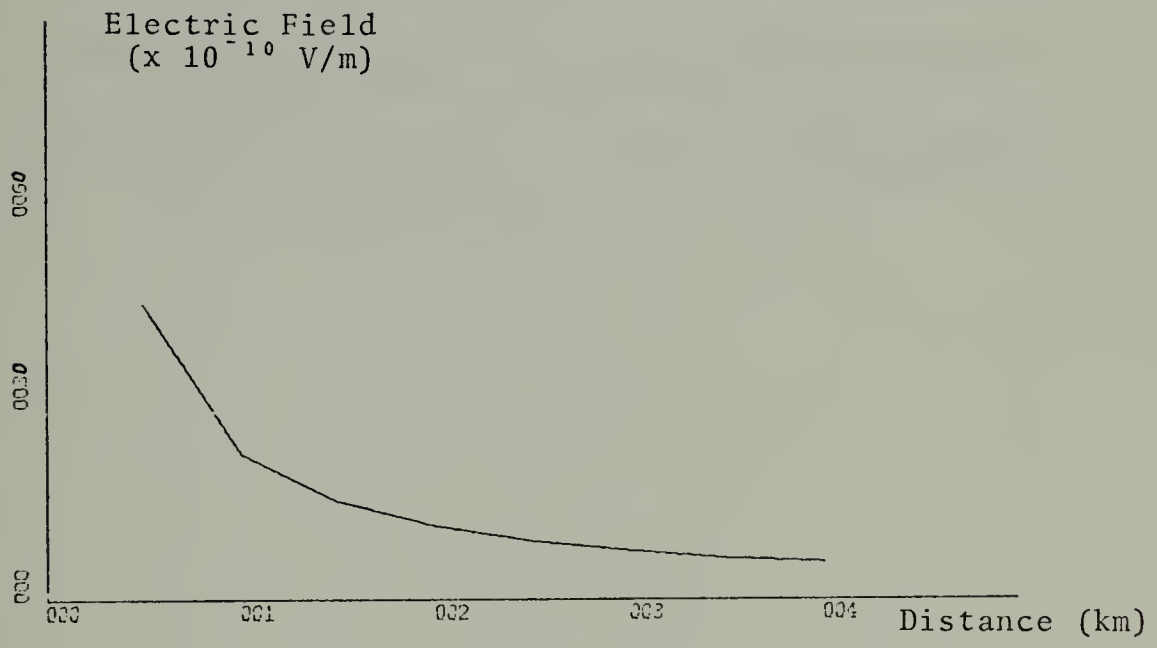

Figure 17. Electric Field vs. Distance from Coil.

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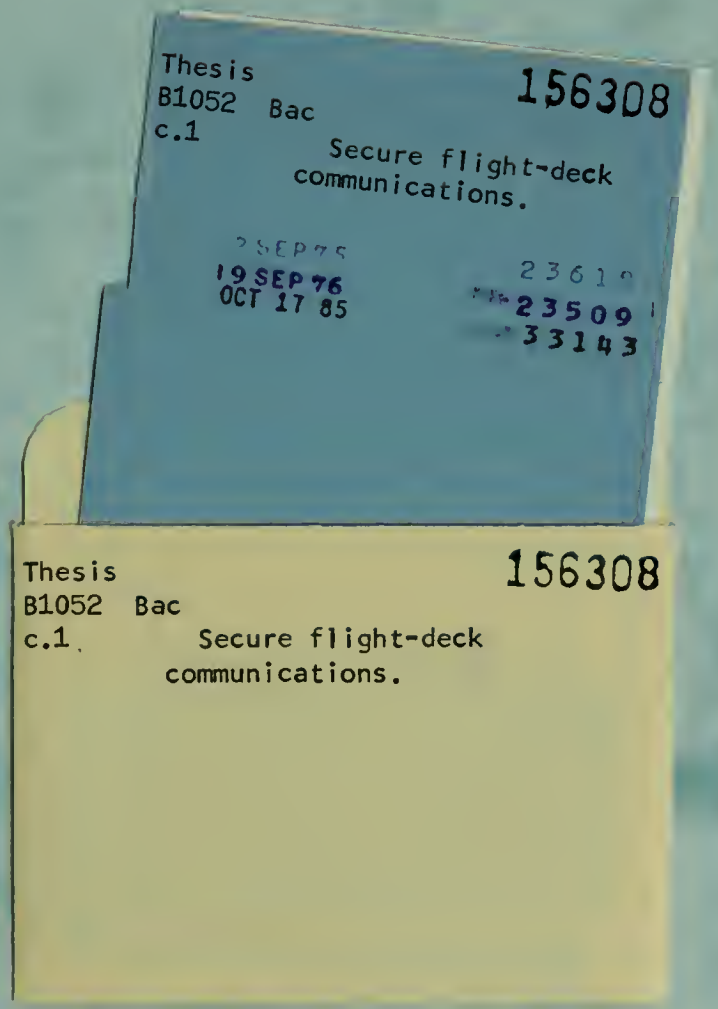
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